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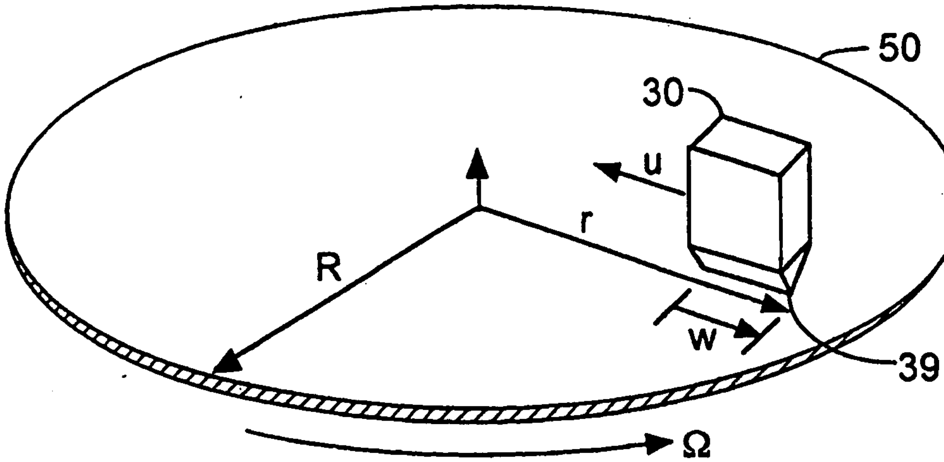
(54) Title: HIGH EFFICIENCY PHOTORESIST COATING



(57) Abstract

An improved method and apparatus for coating semiconductor substrates (50) with organic photoresist polymers by extruding a ribbon of photoresist in a spiral pattern (202) which covers the entire top surface of the wafer (50). The invention provides a more uniform photoresist layer and is much more efficient than are current methods in the use of expensive photoresist solutions. A wafer (50) is mounted on a chuck (114), aligned horizontally and oriented upward. An extrusion head (30) is positioned adjacent to the outer edge of the wafer (50) and above the top surface of the wafer (50) with an extrusion slot (39) aligned radially toward the center of the wafer (50) while photoresist is extruded out the extrusion slot (39). The rotation rate of the wafer (50) and the radial speed of the extrusion head (30) are controlled so that the tangential velocity of the extrusion head (30) with respect to the rotating wafer (50) is a constant.

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TITLE OF THE INVENTION

HIGH EFFICIENCY PHOTORESIST COATING

FIELD OF THE INVENTION

This invention relates to an improved method and apparatus for coating semiconductor substrates with organic photoresist polymers. In particular, this invention relates to an improved method and apparatus for coating semiconductor substrates which provides a more uniform photoresist layer and is much more efficient than are current methods in the use of expensive photoresist solutions.

BACKGROUND OF THE INVENTION

The manufacture of integrated circuits involves the transfer of geometric shapes on a mask to the surface of a semiconductor wafer. Thereafter, the semiconductor wafer corresponding to the geometric shapes, or corresponding to the areas between the geometric shapes, is etched away. The transfer of the shapes from the mask to the semiconductor wafer typically involves a lithographic process. This includes applying a solution of a pre-polymer solution to the semiconductor wafer, the pre-polymer being selected to form a radiation-sensitive polymer which reacts when exposed to ultraviolet light, electron beams, x-rays, or ion beams, for example. The solvent in the pre-polymer solution is removed by evaporation, and the resulting polymer film is then baked. The film is exposed to radiation, for example, ultraviolet light, through a photomask supporting the desired geometric patterns. The images in the photosensitive material are then developed by soaking the wafer in a developing solution. The exposed or unexposed areas are removed in the developing process, depending on the nature of the radiation-sensitive material. Thereafter, the wafer is placed in an etching environment which etches away the areas not protected by the radiation-sensitive material. Due to their resistance to the etching process, the radiation sensitive-materials are also known as photoresists, and the term photoresist is used hereinafter to denote the radiation-sensitive polymers and their pre-polym rs.

The photoresist film thickness required depends on the desired resolution, defect protection, and step coverage. Thicker films provide better adhesion, greater

protection for reactive ion erosion, and improved defect protection. However, thicker films also result in lower resolution because they take longer to expose and develop. Photoresist film thicknesses used in current semiconductor manufacturing may be typically 0.5 to 4 μm thick.

Thickness uniformity of the photoresist layer is an important criterion in the manufacture of integrated circuits. When the radiation is focused through the mask onto the coating, variations in thickness of the coating prevent the precise focus over the entire surface of the wafer which is required to obtain the sharpness necessary to ensure satisfactory reproduction of the geometric patterns on the semiconductor wafer for advanced circuits with line width dimensions approaching 0.25 μm line widths and smaller over a surface. Photoresist film thickness uniformity is required to maintain good transfer of the mask pattern to the photoresist. Uniformity is important to maintain a constant exposure level across the surface of the wafer. Nonuniformities cause position overlay errors when optical steppers attempt to sense alignment marks beneath the photoresist film. Nonuniformities also change the reflectivity of a photoresist deposited over an oxide.

The small critical dimensions of microelectronic devices require photoresist coating thickness typically to be uniform to within 10 Å (3σ). As the critical dimension decreases further, even better uniformities will be required.

The high cost of the photoresist pre-polymer solutions makes it desirable to devise methods of improving the efficiency of the coating process so as to minimize the amount of the polymer solution required to coat a substrate.

Methods which have been used or proposed for coating wafers include dip coating, meniscus coating, spray coating, patch coating, bubble coating, chemical vapor deposition, and spin coating. Only a few of these methods produce photoresist films with the thicknesses and uniformities required for semiconductor production. Of these methods, only spin coating has a production rate fast enough to meet the demands of chip manufacturers. One major shortcoming of spin coating, however, is that it can waste as much as 90%, or more, of the photoresist applied to the wafer surface.

About one million gallons of photoresist are consumed each year at a cost of several hundred million dollars. As the critical dimension of semiconductor devices becomes smaller, new deep UV photoresists will be used. These new photoresists can cost five or more times the cost of the i-line photoresists used currently. Therefore, a new coating method is needed which wastes less photoresist while producing uniform, defect-free coatings at a rate comparable to that of spin coating.

OBJECTS AND SUMMARY OF THE INVENTION

One object of this invention is to provide an improved wafer coating process and apparatus which provide greater coating uniformity across the entire surface of the wafer.

Another object of the invention is to provide an improved wafer coating process and apparatus which provide coating uniformity with less waste and more efficient use of the photoresist.

In a first aspect the invention provides a method of applying a coating of photoresist to a circular semiconductor wafer, the wafer having a top surface, a center, and an outer edge, the method comprising extruding a ribbon of photoresist, the ribbon having a width bounded by outer and inner sides, the ribbon extruded in a spiral pattern which covers the entire top surface of the wafer.

In a second aspect, the invention provides a method of applying a coating of photoresist to a circular semiconductor wafer, the wafer having a top surface, a center, a diameter, and an outer edge, the method comprising the steps of mounting the wafer on a chuck, the top surface of the wafer aligned horizontally and oriented upward; positioning an extrusion head adjacent to the outer edge of the wafer and above the top surface of the wafer, the extrusion head configured to extrude photoresist out an extrusion slot, the extrusion slot having a length bounded by a first end and a second end, the extrusion head positioned with the extrusion slot aligned radially with respect to the wafer, the first end of the extrusion slot located adjacent to the outer edge of the wafer, and the second end of the extrusion slot outside the outer edge of the wafer; rotating the wafer about its center; extruding a ribbon of photoresist from the extrusion slot, the ribbon having a width bounded by outer and inner sides, the width of the ribbon substantially equal to the length of the

slot; and, while extruding photoresist from the extrusion slot, and maintaining the extrusion slot aligned radially with respect to the wafer, moving the extrusion head radially inward from the outer edge of the wafer toward the center of the wafer until the photoresist covers the entire top surface of the wafer.

In a third aspect, the invention provides a method of applying a coating of photoresist to a circular semiconductor wafer, the wafer having a top surface, a center, a diameter, and an outer edge, the method comprising the steps of mounting the wafer on a chuck; positioning an extrusion head at the center of the wafer and above the top surface of the wafer, the extrusion head configured to extrude photoresist out an extrusion slot, the extrusion slot having a length bounded by a first end and a second end, the extrusion head positioned with the extrusion slot aligned radially with respect to the wafer, the second end of the extrusion slot located at the center of the wafer and the first end of the extrusion slot located between the center of the wafer and the outer edge of the wafer; rotating the wafer about its center; extruding a ribbon of photoresist from the extrusion slot, the ribbon having a width substantially equal to the length of the slot; and, while extruding photoresist from the extrusion slot, and maintaining the extrusion slot aligned radially with respect to the wafer, moving the extrusion head radially outward toward the outer edge of the wafer until the second end of the extrusion slot reaches the outer edge of the wafer.

In a fourth aspect, the invention provides an apparatus for applying a coating of photoresist to a circular semiconductor wafer, the wafer having a top surface, a center, a diameter, and an outer edge, the apparatus comprising means for mounting a wafer with the top surface of the wafer aligned horizontally and oriented upward; an extrusion head positioned adjacent to the outer edge of the wafer and above the top surface of the wafer, the extrusion head configured to extrude photoresist out an extrusion slot, the extrusion slot having a length bounded by a first end and a second end, the extrusion head positioned with the extrusion slot aligned radially with respect to the wafer, the first end of the extrusion slot located adjacent to the outer edge of the wafer, and the second end of the extrusion slot outside the outer edge of the wafer; means for rotating the wafer about its center; means for extruding a ribbon of photoresist from the extrusion slot, the ribbon having

a width substantially equal to the length of the slot; and means for, while extruding photoresist from the extrusion slot, and maintaining the extrusion slot aligned radially with respect to the wafer, moving the extrusion head radially inward toward the center of the wafer until the photoresist covers the entire top surface of the wafer.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 illustrates a static dispense method employed to dispense photoresist on a wafer surface in a spin coating process.

FIG. 2 illustrates a forward radial dynamic dispense method employed to dispense photoresist on a wafer surface in a spin coating process.

FIG. 3 illustrates a reverse radial dynamic dispense method employed to dispense photoresist on a wafer surface in a spin coating process.

FIG. 4 is an assembly drawing of a side view of an extrusion head of the invention.

FIG. 5 is a front view of a front plate of an extrusion head of the invention.

FIG. 6 is a front view of a rear plate of an extrusion head of the invention.

FIG. 7 is a front view of a shim of an extrusion head of the invention.

FIG. 8 is a front view of a shim against a back plate.

FIG. 9 is a cross sectional view of an assembled extrusion head of the invention.

FIG. 10 is a perspective view of an assembled extrusion head of the invention.

FIG. 11 is a cross sectional view of the lips of an extrusion head with a substrate moving beneath the lips of the extrusion head.

FIGs. 12, 13 and **14** are a front view, top view and rear view, respectively of an extrusion spin coating assembly of the invention.

FIG. 15 is a block diagram of an embodiment of a control system in the extrusion spin coating assembly of the invention.

FIGs. 16, 17, 18 and **19** illustrate the configuration of an extrusion spin coating assembly during several steps of the extrusion spin coating process of the invention.

FIG. 20 is a diagram which illustrates certain parameters of extrusion spin coating motion according to the invention.

FIG. 21 illustrates an extrusion spin coating spiral pattern according to the invention.

DETAILED DESCRIPTION OF THE INVENTION

FIGs. 1, 2 and **3** shows three primary methods currently employed to dispense photoresist on a wafer surface in a spin coating process. The method depicted in **FIG. 1** is referred to as "static dispense." In static dispense, the photoresist is dispensed directly into the center of a stationary wafer **10**, producing a circular pool of photoresist **12**. Alternatively, the entire surface of the wafer **10** may be flooded with photoresist. Often, the wafer **10** is rotated slowly after a static dispense to begin spreading the photoresist **12** over the wafer **10** surface.

The methods illustrated in **FIGs. 2** and **3** are referred to as "dynamic dispenses," because the wafer **10** is rotating slowly while the photoresist **14, 16** is dispensed. During forward radial dispense, illustrated in **FIG. 2**, the dispense nozzle **20** is initially located at the center of the wafer **10** and moves radially outward as the photoresist **14** is deposited. For reverse radial dispense, illustrated in **FIG. 3**, the dispense nozzle begins at the outer edge of the wafer and moves radially inward. In both **FIGs. 2** and **3** the dispense nozzle **20** is illustrated at the end of travel after

having deposited photoresist on the slowly spinning wafer **10**. Both forward and reverse radial dispense produce a spiral pattern **14, 16** of photoresist. The g ometry of the spiral **14, 16**, i.e. number of turns of the spiral and volume of photoresist per unit length along the spiral, is determined by the angular rotation of the wafer **10**, the radial velocity of the nozzle **20** with respect to the wafer **10**, and the volumetric flow of the photoresist during the dispense. Dynamic dispenses use less photoresist, but static dispenses produce a more uniform film.

After the photoresist is deposited on the wafer, the wafer is accelerated to create a centrifugal force which spreads the photoresist toward the edge of the wafer. The wafer may be spun at an intermediate speed for a few seconds before being accelerated to the final high-speed spin. When the bulk of the photoresist reaches the edge of the wafer, most of the photoresist is flung off in many tiny droplets. It has been shown that while the acceleration rate does not affect the final film thickness, higher acceleration rates do tend to produce more uniform films.

Once the wafer is spun up to the final high speed, the wafer continues to spin to cause the photoresist to reach the desired thickness. Photoresist continues to flow outward and off the wafer in concentric waves. Simultaneously, the solvent in the photoresist evaporates quickly because of high convection over the wafer surface. As the solvent fraction in the photoresist decreases, the viscosity of the photoresist gradually increases, causing the outward flow of photoresist to diminish until it almost ceases. Subsequent thinning of the photoresist comes almost entirely from solvent evaporation. When the solvent is mostly evaporated, typically after about 30 seconds, spinning is stopped, and the wafer is soft baked at a high temperature to evaporate the remaining solvent from the photoresist.

In each of the dispense methods depicted in **FIGs. 1**, **2** and **3**, the photoresist is dispensed onto the wafer in a thick puddle or ribbon, and must be spread by some means, e.g. slow spin, to spread the photoresist to cover the wafer and to reduce the photoresist to a thin layer. In the method of the invention, the photoresist is applied in a thin uniform layer over the entire surface of the wafer. This eliminates the need for the slow spin step, and requires less photoresist to be deposited on the wafer to achieve the desired final thickness and uniformity.

The method of the invention employs extrusion slot coating to dispense a thin ribbon of photoresist over the entire surface of the wafer. Extrusion slot coating is a member of the class of pre-metered coating methods. With extrusion slot coating, the coating thickness can be controlled by the photoresist dispense rate, the efficiency can be near 100%, and the thickness uniformity is very good.

In extrusion slot coating, the photoresist is extruded onto the wafer through a narrow slot. **FIGs. 4-11** illustrate an embodiment of an extrusion head **30** which may be used in the invention. The extrusion head **30** may also be referred to as an extrusion die. **FIG. 4** shows a side assembly view of the extrusion head **30** which is constructed of a stainless steel U-shaped shim **31** sandwiched between a stainless steel front plate **32** and a stainless steel back plate **33**. **FIGs. 5**, **6** and **7** show a front view of the front plate **32**, back plate **33**, and shim **31**, respectively. **FIG. 8** shows a front view of the shim **31** against the back plate **33**. Referring to **FIG. 4**, the front plate **32** and back plate **33** are grounded and polished on their inner edges, facing the shim **31**, to provide good seal with the shim **31** and a smooth surface for extrusion. Photoresist enters the extrusion head **30** through a port **34** in the top of the back plate **33**. The port **34** directs the photoresist through a tube **35** to a flow channel **36** (**FIGs. 4**, **6**). The flow channel **36** is as wide as the opening of the "U" **37** of the shim **31** (**FIGs. 7**, **8**).

FIG. 9 is a sectional view of the extrusion head **30** illustrated in **FIG. 4**. The void created by the u-shape of the shim **31** leaves a narrow gap **38** between the front plate **32** and back plate **33** through which photoresist can flow. At the base of the extrusion head **30**, the gap **38** continues downward between two narrow "lips" **41**, **42** which extend the inner surface of the front plate **32** and back plate **33**.

FIG. 10 is a perspective view of the extrusion head illustrated in **FIG. 4**. The gap **38** extends across the opening of the "U" **37** (**FIGs. 7**, **8**) of the shim **31** to form an extrusion slot **39** in the extrusion head **30**.

FIG. 11 is a cross sectional view of the lips **41**, **42** of an extrusion head **30** with a substrate **50** moving beneath the extrusion lips **41**, **42**. Photoresist is extruded out the slot **39** at the base of the lips **41**, **42** onto the top surface **51** of the substrate **50**. The width of the gap **38** between the front plate **32** and rear plate **33**,

indicated as d, is equal to the thickness of the shim **31** (**FIGs. 4, 9**). The coating gap between the lips **41, 42** and the substrate **50** is filled with a bead **46** of coating fluid coming from the slot **39**. When the substrate **50** is moved perpendicular to the slot **39**, keeping the coating gap constant, fluid is drawn out of the bead **46** and remains as a thin film on the substrate **50**. The width of the extruded film, w (**FIGs. 19, 20**) is approximately equal to the length of the extrusion slot **39**, i.e. the opening of the "U" **37** of the shim **31** (**FIGs. 7, 8**). The average thickness of the extruded film, h, is

$$h = \frac{Q}{wv}$$

where v is the coating speed, and Q is the fluid dispense rate. The menisci **44, 45** at the leading and trailing edges of the coating bead **46** are pinned to the corners of the extrusion head lips **41, 42**. The corners of the extrusion head lips **41, 42** should have a radius of curvature less than approximately 50 μm to keep the menisci **44, 45** pinned. The capillary, viscous, and inlet pressures in the coating bead **46** must balance the external pressure to maintain stability in the coating bead **46**. A slight vacuum at the leading edge of the coating bead **46** can be used to stabilize the coating bead **46** when coating thinner films or at higher coating speeds. The extrusion head lips **41, 42** are normally of equal length ($G_1 = G_2$) and the extrusion head **30** is perpendicular to the substrate **50**. For very thin coatings, however, it is sometimes beneficial to have one of the lips extend beyond the other ($G_1 \neq G_2$) or to have the extrusion head **30** slightly tilted from perpendicular to the substrate **50**, thereby tilting the coating slot **39** with respect to the substrate **50**.

The description of the extrusion spin coating assembly **100** will be with reference to **FIGs. 12, 13** and **14**, which illustrate front, top and rear views, respectively, of an extrusion spin coating assembly **100** according to the invention. Components of the extrusion spin coating assembly **100** illustrated in **FIGs. 12, 13** and **14** include a coating module **110** and a positioning system **130**. Not illustrated in **FIGs. 12, 13** and **14**, but described with reference to **FIG. 15**, is a control system **210** which includes a positioning controller **220** and a spinner controller **280**.

The coating module **110** includes a spinner assembly **111** which includes a spinner servomotor (not illustrated, reference numeral **113** in **FIG. 15**) connected to

a vertical shaft **112**. The vertical shaft **112** supports a Teflon vacuum chuck **114**. The spinner assembly **111** can be moved vertically using a chuck elevator servomotor (not illustrated, reference numeral **115** in **FIG. 15**). The chuck elevator servomotor is equipped with an elevator motor brake (not illustrated, reference numeral **135** in FIG. **15**). With the spinner assembly **111** at its lowest position, the chuck **114** is surrounded by a catch cup **116** (sectional view illustrated). The catch cup **116** is a circular cup having an open top **117**. The upper portion **120** of the cup wall **118** tilts inward to facilitate retaining waste photoresist within the catch cup **116**. The catch cup **116** serves three purposes. The catch cup **116** catches and drains waste photoresist out a liquid waste drain **122**. The catch cup has an exhaust vent **118** through which evaporated solvent is removed. The catch cup **116** directs the flow of air over a spinning wafer to avoid turbulence. Both the exhaust vent **118** and waste drain **122** exit the bottom **124** of the catch cup **116**. Means for removing waste photoresist and exhausted vapors are well known to those skilled in the art and are therefore not illustrated.

The spinner assembly **111** has a centering device including eight Teflon pins **138** for centering wafers on the chuck **114**, and three vertical pins (not illustrated) for supporting loose wafers before and after processing. The centering pins **138** are controlled by a centering solenoid (not illustrated, reference numeral **119** in **FIG. 15**). Sensors on the coater module **110** indicate chuck **114** vertical home position (not illustrated, reference numeral **121** in **FIG. 15**), vacuum state (on/off) (not illustrated, reference numeral **123** in **FIG. 15**), and centering pin position (not illustrated, reference numeral **125** in **FIG. 15**). These features of the coating module **110** are well know to those skilled in the art and are therefore not illustrated.

A coater module **110** suitable for use with the invention is a 90SE coater module which is commercially available from Silicon Valley Group, Inc. The 90SE coater module is one component of a 90SE Wafer Processing track also commercially available from Silicon Valley Group, Inc.

The positioning system **130** is supported by an aluminum baseplate **132** which is mounted above the coater module **110**. The baseplate **132** has a center cut-out **134** positioned over the coater module **110**. First and second vertical

support plates **134**, **136** mounted above the baseplate support a cross-support **137** on which a two-axis positioning system **150** is mounted. The positioning system **150** includes an x-axis positioning table **152** and a z-axis positioning table **162**. The x-axis positioning table **152** includes an x-axis table motor **154** and x-axis table base **156**. Likewise, the z-axis positioning table **162** includes a z-axis table motor **164** and z-axis table base **166**. The z-axis positioning table **162** also includes a z-axis brake (not illustrated, reference numeral **133** in **FIG. 15**). The z-axis positioning table **162** is mounted on the carriage **158** of the x-axis positioning table **152**. The x-axis positioning table **152** moves in a horizontal plane, parallel to the surface **51** of a wafer **50** mounted on the chuck **114**, and the z-axis positioning table **162** moves in a vertical direction perpendicular to the plane of the surface **51** of a wafer **50** mounted on the chuck **114**. A positioning system suitable for use in the x-axis and z-axis positioning tables **152**, **162** of the invention is the Parker Daedal Motion Table driven by 5-pitch ball screws.

An extrusion head **30** is mounted at the bottom of an aluminum extrusion head support **172** which, in turn, is mounted on the z-axis positioning table **162**. The z-axis positioning table **162** has sufficient range of motion to move the extrusion head **30** from a position above the base plate **132**, down, through the center cut-out **134** in the baseplate **132**, to the proximity of a wafer **50** on the chuck **114**.

An optical sensor **174** is mounted on the extrusion head support **172**. The optical sensor **174** is used to measure the gap between the extrusion head **30** and a wafer **50** mounted on the chuck **114**. A sensor suitable for use in an embodiment of the invention is a Philtec RC140L reflectance compensated optical displacement sensor. The optical sensor **174** shines a light on the surface of the wafer **50**, measures the reflected light, and generates a voltage proportional to the intensity of the measured light. The spot size of the Philtec sensor is 6mm and has a bandwidth from DC to 100 Hz. The voltage-distance curve of the Philtec sensor is generally non-linear, but has a linear region when the sensor-wafer distance is between, for example, 5.51 and 6.17 mm (0.217 and 0.243 inch). The optical sensor **174** is positioned on the extrusion head support **172** so that all measurements fall within the linear range of the optical sensor **174**.

Means for controlling flow of the photoresist includes a photoresist pump (not illustrated) and a photoresist shutoff valve **129**. Such arrangements are well know to those skilled in the art, and therefore is not fully illustrated in **FIGs. 12, 13** or **14.** However, the following description of the control system **210** of the extrusion spin coating assembly **100** includes reference to the photoresist pump (not illustrated, reference numeral **127** in **FIG. 15**) and the photoresist shutoff valve **129.**

FIG. **15** is a block diagram which illustrates an embodiment of a control system **210** suitable for controlling the extrusion spin coating assembly **100** of the invention. The control system **210** includes a computer **212**, a positioning controller **220** and a spinner controller **280**. The computer **212** downloads programs to the positioning controller **220**, the spinner controller **280** and the photoresist dispense pump **127** via serial interfaces **213, 214, 215**. The positioning controller **220** sends commands to the photoresist dispense pump **127** to start and stop photoresist flow and to control the photoresist shutoff valve **129**. The positioning controller **220** also controls the position of the x-axis positioning table **152** via the x-axis motor **154** and z-axis positioning table **162** via the z-axis motor **164**, and the chuck elevator servomotor **115**. The positioning controller **220** receives the output of the optical sensor **174**, calculates the distance between the extrusion head **30** and the wafer **50**, and uses the results to control the z-axis positioning table **162** via the z-axis motor **164**.

A computer suitable for use in the control system **210** is an IBM–compatible PC. Suitable for use as the positioning controller **220** is the Parker Compumotor AT6450 Servo Controller, including the optional ANI analog input PC card and the AUX board. Suitable for use as the spinner controller **280** is The Pacific Scientific SC 755. Although the computer **212**, positioning controller **220** and spinner controller **280** are shown separately in the block diagram of **FIG. 15**, in an embodiment which includes the Parker Compumotor AT6450 and Pacific Scientific SC755 controllers, the Compumotor AT6450 plugs into the motherboard of the PC. The invention also contemplates an embodiment in which both the positioning controller **220** and spinner controller **280** functions ar provided by a single, combined controller.

The positioning controller **220** includes a positioning controller processor and several inputs and outputs. The inputs and outputs include a 14-bit analog to digital (A/D) converter, several discrete digital inputs and outputs, and servomotor outputs (the processor and inputs and outputs are well known to those skilled in the art and are not individually illustrated). The output of the optical sensor **174** is coupled to the A/D converter input **224**. The positioning controller **220** discrete digital inputs are optically isolated interfaces, and include a chuck position home indicator input **242** coupled to the chuck position home sensor **121**; a vacuum on/off status indicator input **244** coupled to the vacuum on/off sensor **123** on the vacuum chuck **114**; a centering pin in/out position indicator input **246** coupled to the centering pin position sensor **125**; and one or more manual positioning command inputs **248** coupled to operator manual positioning switches **126**.

The positioning controller **220** outputs include an x-axis servomotor output **226** which is coupled to the x-axis servomotor **154**; a z-axis servomotor output **228** which is coupled to the z-axis servomotor **164**; and an elevator motor output **230** which is coupled to the elevator servomotor **115**.

The positioning controller **220** discrete digital outputs include a photoresist valve on/off output **254** which is coupled to the photoresist shutoff valve **129**; a centering solenoid output **256** which is coupled to the centering solenoid **119** which controls the centering pins **138**; a vacuum solenoid output **258** which is coupled to the vacuum solenoid **131**; a z-axis motor brake output **260** which is coupled to the z-axis brake **133** in the z-axis positioning table **162**; an elevator motor brake output **262** which is coupled to the elevator motor brake **135**; a trigger output **264** to the photoresist dispense pump **127**; and logical outputs **266** to the spinner controller **280**.

The spinner controller **280** runs the coating and spin cycles in response to signals received from the positioning controller **220**. The spinner controller **280** includes a spinner controller processor, a servomotor output, and an encoder (the processor and encoder are well known to those skilled in the art and are not individually illustrated). The spinner controller **280** outputs include a spinner motor output **286** which is coupled to the spinner motor **113** The output of the spinner

controller **280** also includes a simulated encoder signal **288** which is coupled to the positioning controller. The simulated encoder signal **288** allows electronic gearing of the spinner motor **113** speed to control the x-axis positioning of the extrusion head **30** performed by the positioning controller **220**.

The extrusion head **30** and the positioning tables **152**, **162** must be aligned with respect to a wafer **50** mounted on the chuck **114** to obtain reliable coating. Three alignments are required. These alignments will be described with reference to **FIGs. 12**, **13** and **14**. A first alignment adjusts the path of the extrusion slot **39** so that the extrusion slot **39** passes directly over the center of a wafer **50** mounted on the chuck **114**. This alignment is needed to completely cover the center area of the wafer **50**. The extrusion head **30** is positioned over the center of the wafer **50** by sliding the vertical support plates **134**, **136** forward or backward over the base plate **132**. The motion of the vertical support plates **134**, **136** is constrained by a guide on the base plate **132**. Adjustment bolts at the rear of each of the vertical support plates **134**, **136** allow fine tuning of the position of the vertical support plates **134**, **136** before the vertical support plates **134**, **136** are fastened into place.

The second alignment adjusts the angle of the x-axis with respect to the wafer surface **51**. This alignment maintains a constant gap between the wafer **50** and the extrusion head **30** as the x-axis positioning table **152** changes position. The angle of the x-axis with respect to the wafer surface **51** can be changed by rotating the cross-support **138** about a first pivot **179** at one end of the cross-support **137**. Fine and coarse adjustment bolts **184**, **186** allow adjustments of the angle between the x-axis and the wafer surface **51** of 1.64×10^{-5} radians per turn of the fine adjustment bolt **184**. The angle of the x-axis with respect to the wafer surface **51** can be determined by scanning across the wafer surface **51** with the optical sensor **174**. During the scan, with the z-axis fixed, measurements of the optical sensor **174** output and the x-position are recorded. A linear regression of these data pairs provides the angle between the wafer surface **51** and the x-axis.

The third alignment adjusts the bottom edge of the extrusion head **30**, i.e. the extrusion slot **39**, until it is parallel with the x-axis and the wafer surface **51**. This alignment is crucial for maintaining a constant gap across the width of the extrusion

head **30**. The angle between the bottom edge of the extrusion head **30** and the x-axis can be adjusted using a wafer-extruder parallelism adjustment bolt **176**. The wafer-extruder parallelism adjustment bolt **176** pivots the extrusion head support **172** about a wafer-extruder parallelism adjustment pivot **178** at the base of the z-axis positioning table **162**. The angle between the x-axis and the bottom of the extrusion head **30** can be measured using a linear variable differential transformer (LVDT) sensor. The LVDT sensor is secured to the wafer surface **51** with the measurement tip pointing vertically up. Next, the extrusion head **30** is lowered until the lips **41**, **42** of the extrusion head **30** move the LVTD sensor to a reference position. After the x-axis and z-axis positioning table **152**, **162** positions are recorded, the procedure is repeated for several other positions along the extrusion head lips **41**, **42**. The slope of the extrusion head **30** with respect to the x-axis is determined using a linear regression of these data pairs.

The optical sensor **174** may be calibrated in a two-step process. First, a voltage offset (i.e., zero-gap bias) voltage is determined by measuring the output voltage of the optical sensor **174** at several small gap distances using precision shims placed between the extrusion head **30** and the wafer surface **51**. A linear regression analysis of the gap distance and sensor voltage data is used to calculate the voltage offset (i.e., sensor voltage at a zero gap). Second, the relationship of the sensor voltage and the height of the extrusion slot **39**, in the linear range of the optical sensor **174**, is determined by raising the extrusion slot **39** in selected increments (e.g., 10 encoder counts equals 12.7 μm) and recording the sensor voltage at each position. A linear regression of the data pair provides the slope of the curve representing sensor voltage versus z-axis position of the extrusion slot **39**. The extrusion head **30** must be aligned with respect to the x-axis and wafer surface, as described above, prior to calibrating the optical sensor **174** so that errors will not arise from the angle between the extrusion head **30** and the wafer surface **51**.

The extrusion spin coating process will be described with reference to **FIGs. 16 - 19**. The alignment and calibration procedures described above may be performed periodically or prior to a series of runs as determined to be necessary based on experience with the equipment used.

Referring to **FIG. 16**, the vacuum chuck **114** is raised through the cut out **134** in the base plate **132**, and the wafer **50** is placed on the chuck **114**. The wafer **50** is centered on the chuck **114** using the centering pins **138** (**FIG. 13**). The chuck vacuum (not illustrated) is turned on to secure the wafer **50**. The chuck **114** is lowered, lowering the wafer **50** into the coating position, and the extrusion head **30** is lowered into position at the edge of the wafer **50** with the desired gap between the wafer **50** and the extrusion head lips **41**, **42** as illustrated in **FIG. 17**. The chuck **114** is then rotated at an initial rotational speed which is the desired coating speed. The photoresist shutoff valve **129** is opened and the photoresist pump **127** is triggered to begin dispensing photoresist. The extrusion head **30** is moved radially with respect to the wafer **50**. As the extrusion head **30** moves toward the center of the wafer **50**, the rotational speed of the chuck **114** is increased and the extrusion head speed is increased at a rate proportional to the increase in the rotational speed in order to maintain the coating speed of the extrusion head **30** over the wafer **50** constant. When the leading edge of the extrusion head **30** reaches the center of the wafer **50**, illustrated in **FIG. 18**, the speed of rotation of the wafer **30** is held constant until the trailing edge of the extrusion head **30** reaches the center of the wafer **50**. When the entire wafer **50** is covered with photoresist, the photoresist pump **127** is triggered to stop dispensing photoresist, and the photoresist shutoff valve **129** is closed. Typically, it is necessary to continue extruding photoresist and continue moving the extrusion head **30** until the trailing edge of the extrusion head **30** reaches the center of the wafer **50** in order to cover the entire wafer **50** with photoresist. When the photoresist pump **127** and shutoff valve **129** are triggered to stop dispensing photoresist, a residual amount of photoresist which is already in the extrusion head **30** (and possibly also in tubing leading to the extrusion head **30**) may continue to flow and be deposited on the wafer **50**. In such cases, the photoresist pump **127** and shutoff valve **129** may be triggered to stop dispensing photoresist a short time prior to covering the entire wafer **50**, thereby allowing such residual photoresist to finish covering the wafer **50**.

The chuck **114** then lowers the wafer **50** into the catch cup **116**, and the extrusion head **30** is raised from the coating area as illustrated in **FIG. 19**. The wafer **50** is then spun at high speed to remove excess photoresist and achieve the

desired coating uniformity. The chuck **114** stops spinning and is raised through the center cut out **134** in the base plate **132**. The vacuum is turned off and the wafer **50** removed from the chuck **114**.

FIG. 20 is a diagram which illustrates certain parameters of extrusion spin coating motion according to the invention. In **FIG. 20**, a wafer **50**, has a radius R, and is rotating about its center at an angular velocity of Ω. An extrusion head **30** is above the wafer **50**, with the extrusion slot **39** radially aligned with respect to the wafer **50**. The extrusion slot **39** has a width w, and is moving radially with respect to the wafer **50** at a velocity u. The distance between the center of the wafer **50** and the trailing edge of the extrusion head **30** is r.

The tangential velocity of any point on the surface of the wafer **50**, at a distance r from the axis of rotation shown in **FIG. 20** is:

$$v = \Omega r$$

With the trailing edge of the extrusion head **30** at a distance r from the axis of rotation, a spiral extrusion pattern can be made by moving the extrusion head **30** inward one length of the extrusion slot **39** for each revolution of the wafer **50**, The extrusion head **30** speed along the diameter of the wafer **50** is then:

$$u = \frac{\Omega w}{2\pi}$$

Solving for Ω and substituting yields:

$$u = \frac{wv}{2\pi r}$$

For radially inward motion, $u = -dr/dt$, and a differential equation for the position of the extrusion head can be obtained as follows:

$$\frac{dr}{dt} = -\frac{wv}{2\pi r}$$

Integrating this equation using the initial condition $r = r_0$ at time $t=0$ yields:

$$r = \left(r_o^2 - \frac{wvt}{\pi} \right)^{1/2}$$

The wafer rotation speed can be expressed as a function of time as:

$$\Omega = \frac{v}{\left(r_o^2 - \frac{wvt}{\pi} \right)^{1/2}}$$

and the head speed can be expressed as a function of time as:

$$u = \frac{wv}{2\Pi \left(r_o^2 - \frac{wvt}{\pi} \right)^{1/2}}$$

FIG. 21 illustrates an extrusion spin coating spiral pattern **202** according to one aspect of the invention. The spiral pattern **202** results from the extrusion head **30** starting at the outer edge **52** of the wafer **50** and moving radially inward toward the center of the wafer **50**. A first shaded region **204** represents wasted photoresist at the outer edge of the wafer **50**, and a second shaded region **206** represents a double thickness of photoresist extruded in the center region of the wafer **50**. It is necessary to start the process with the extrusion head **50** just off the outer edge **52** of the wafer **50** to cover the entire outer edge **52** with the extruded spiral pattern **202** without unnecessary overlap or double thickness around the outer edge **52** of the wafer **50**. This results in the first shaded region **204** of wasted photoresist. Likewise, it is necessary to continue to extrude photoresist after the leading edge of the extrusion head **30** reaches the center of the wafer **50** until the entire wafer **50** is covered. Typically, it will be necessary to continue the process until the trailing edge of the extrusion head **30** reaches the center to cover the entire center region of the wafer **50**. The overlap in the second shaded region **206** at the center of the wafer **50** is inevitable because of the finite width of the extrusion head **30**. However, the amount of wasted and excess photoresist is relatively small, and the efficiency of the extrusion spin coating process far exceeds the efficiency of prior spin coating processes.

FIG. 21 illustrates an extrusion spin coating spiral pattern which results from starting the extrusion head at the outer edge of the wafer and, while spinning the wafer, moving the extrusion head radially inward toward the center of the wafer. The method and apparatus of the invention may instead start the extrusion head at the center of the wafer and move the extrusion head radially outward toward the outer edge of the wafer.

It will be readily apparent to those skilled in the art that this invention is not limited to the embodiments described above. Different configurations and embodiments can be developed without departing from the scope of the invention and are intended to be included within the scope of the claims.

THE INVENTION CLAIMED IS:

1. A method of applying a coating of photoresist to a circular semiconductor wafer, the wafer having a top surface, a center, and an outer edge, the method comprising extruding a ribbon of photoresist, the ribbon having a width, the ribbon extruded in a spiral pattern which covers the entire top surface of the wafer.

2. A method according to Claim 1, wherein the ribbon of photoresist is extruded in a spiral pattern beginning at the outer edge of the wafer and ending at the center of the wafer.

3. A method according to Claim 1, wherein the ribbon of photoresist is extruded in a spiral pattern beginning at the center of the wafer and ending at the outer edge of the wafer.

4. A method according to Claim 1, wherein the width of the photoresist ribbon is between about one tenth and about one third of the diameter of the semiconductor wafer.

5. A method of applying a coating of photoresist to a circular semiconductor wafer, the wafer having a top surface, a center, a diameter, and an outer edge, the method comprising the steps of

(a) mounting the wafer on a chuck, the top surface of the wafer aligned horizontally and oriented upward,

(b) positioning an extrusion head adjacent to the outer edge of the wafer and above the top surface of the wafer, the extrusion head configured to extrude photoresist out an extrusion slot, the extrusion slot having a length bounded by a first end and a second end, the extrusion head positioned with the extrusion slot aligned radially with respect to the wafer, the first end of the extrusion slot located adjacent to the outer edge of the wafer, and the second end of the extrusion slot outside the outer edge of the wafer,

(c) rotating the wafer about its center,

(c) extruding a ribbon of photoresist from the extrusion slot, the ribbon having a width which is substantially equal to the length of the slot, and

(e) while extruding photoresist from the extrusion slot, and maintaining the extrusion slot aligned radially with respect to the wafer, moving the extrusion head radially inward from the outer edge of the wafer toward the center of the wafer until the photoresist covers the entire top surface of the wafer.

6. A method according to Claim 5, wherein the length of the extrusion slot is between about one tenth and about one third of the diameter of the semiconductor wafer.

7. A method according to Claim 5, wherein the photoresist is extruded from the extrusion slot at a rate which is a constant extrusion rate.

8. A method according to Claim 5, wherein, with the wafer rotating at a rotational speed, and the extrusion head moving at a radial speed, the motion of the radially moving extrusion head with respect to the rotating wafer is at a tangential velocity which is a constant tangential velocity.

9. A method according to Claim 5, wherein step (e) comprises maintaining the extrusion slot a predetermined distance above the top surface of the wafer.

10. A method according to Claim 9, wherein step (e) comprises determining the distance between the extrusion slot and the top surface of the wafer, and adjusting the position of the extrusion slot to maintain the predetermined distance.

11. A method according to Claim 10, wherein step (e) comprises determining the distance between the extrusion slot and the top surface of the wafer using an optical sensor.

12. A method according to Claim 5, wherein the photoresist ribbon is extruded in a spiral pattern which covers the entire top surface of the wafer.

13. A method according to Claim 5, comprising the steps of
(f) removing the extrusion head, and
(g) rotating the wafer at high speed.

14. A method of applying a coating of photoresist to a circular semiconductor wafer, the wafer having a top surface, a center, a diameter, and an outer edge, the method comprising the steps of

a. mounting the wafer on a chuck,

b. positioning an extrusion head at the center of the wafer and above the top surface of the wafer, the extrusion head configured to extrude photoresist out an extrusion slot, the extrusion slot having a length bounded by a first end and a second end, the extrusion head positioned with the extrusion slot aligned radially with respect to the wafer, the first end of the extrusion slot located at the center of the wafer and the second end of the extrusion slot located between the center of the wafer and the outer edge of the wafer,

c, rotating the wafer about its center,

d. extruding a ribbon of photoresist from the extrusion slot, the ribbon having a width substantially equal to the length of the slot, and

e. while extruding photoresist from the extrusion slot, and maintaining the extrusion slot aligned radially with respect to the wafer, moving the extrusion head radially outward toward the outer edge of the wafer until the photoresist covers the entire top surface of the wafer.

15. An apparatus for applying a coating of photoresist to a circular semiconductor wafer, the wafer having a top surface, a center, a diameter, and an outer edge, the apparatus comprising

means for mounting a wafer with the top surface of the wafer aligned horizontally and oriented upward,

an extrusion head positioned adjacent to the outer edge of the wafer and above the top surface of the wafer, the extrusion head configured to extrude photoresist out an extrusion slot, the extrusion slot having a length bounded by a first end and a second end, the extrusion head positioned with the extrusion slot aligned radially with respect to the wafer, the first end of the extrusion slot located adjacent to the outer edge of the wafer,

and the second end of the extrusion slot outside the outer edge of the wafer,

means for rotating the wafer about its center,

means for extruding a ribbon of photoresist from the extrusion slot, the ribbon having a width substantially equal to the length of the slot, and

means for, while extruding photoresist from the extrusion slot, and maintaining the extrusion slot aligned radially with respect to the wafer, moving the extrusion head radially inward toward the center of the wafer until the photoresist covers the entire top surface of the wafer.

16. An apparatus according to Claim 15, comprising means for rotating a wafer at a rotational speed, and moving the extrusion head at a radial speed, such that the motion of the radially moving extrusion head with respect to the rotating wafer is at a tangential velocity which is a constant tangential velocity.

17. An apparatus according to Claim 15, comprising means for maintaining the extrusion slot a predetermined distance above the top surface of the wafer.

18. An apparatus according to Claim 17, wherein the means for maintaining the extrusion slot a predetermined distance above the top surface of the wafer comprises means for determining the distance between the extrusion slot and the top surface of the wafer, and means for adjusting the position of the extrusion slot to maintain the predetermined distance.

19. An apparatus according to Claim 18, wherein the means for measuring the distance between the extrusion slot and the top surface of the wafer comprises an optical sensor.

20. An apparatus according to Claim 15, comprising means for extruding a ribbon of photoresist in a spiral pattern beginning at the center of the wafer and ending at the outer edge of the wafer.

21. An apparatus according to Claim 15, wherein th width of the extrusion slot is between about one tenth and about one third of the diameter of the semiconductor wafer.

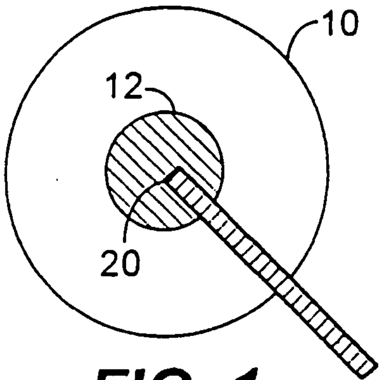


FIG. 1
Prior Art

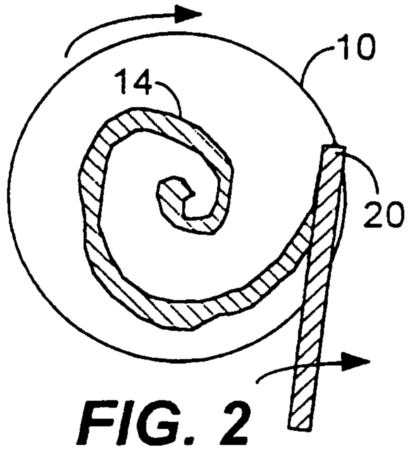


FIG. 2
Prior Art

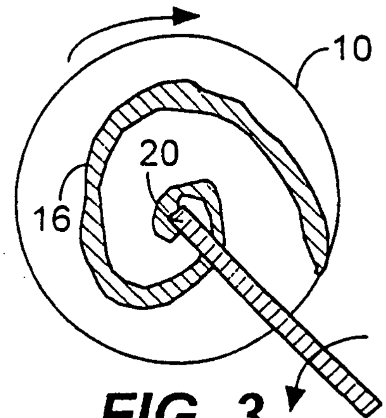


FIG. 3
Prior Art

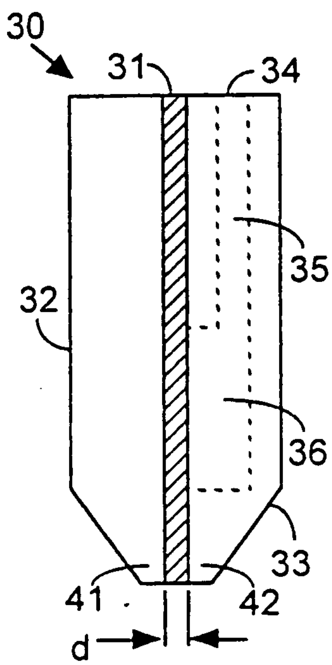


FIG. 4

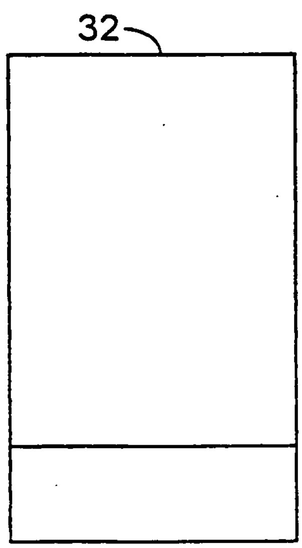


FIG. 5

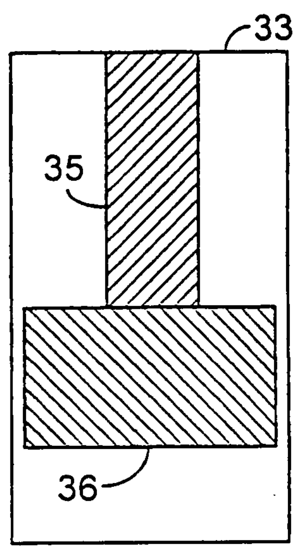


FIG. 6

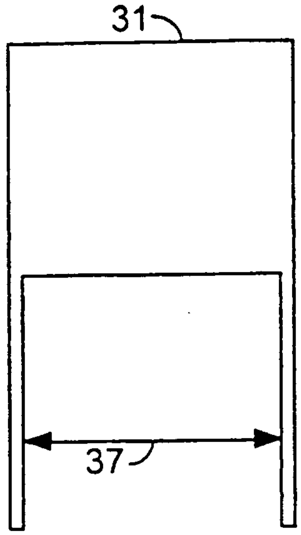


FIG. 7

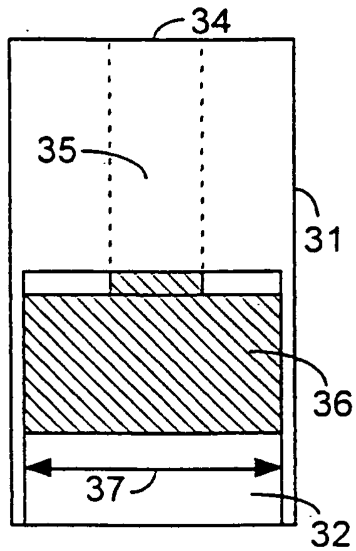


FIG. 8

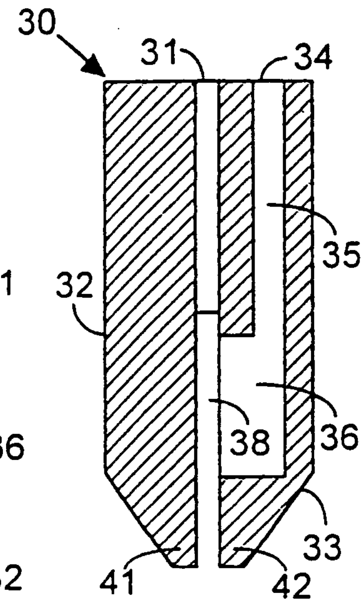


FIG. 9

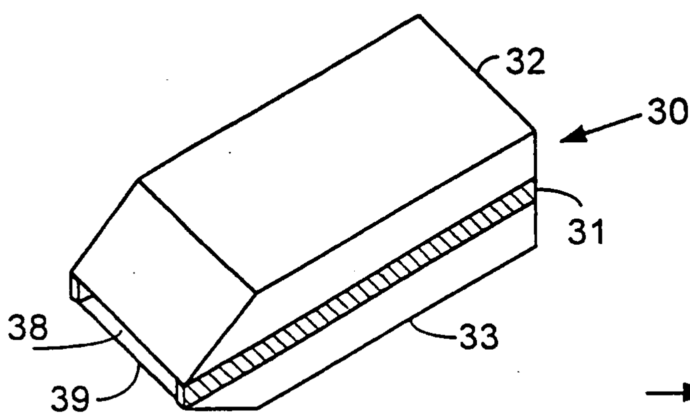


FIG. 10

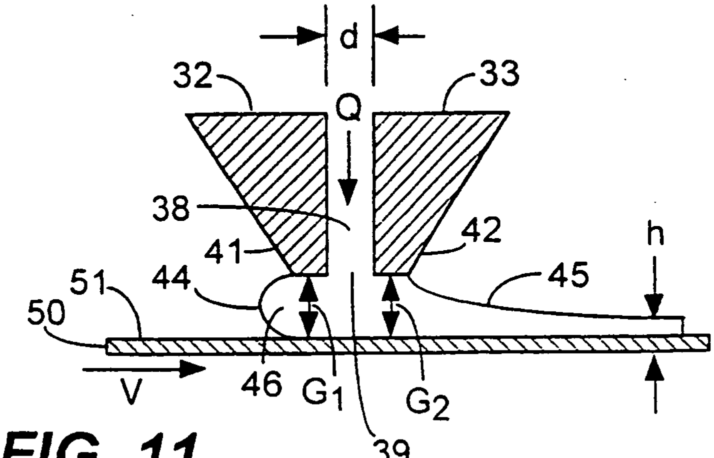
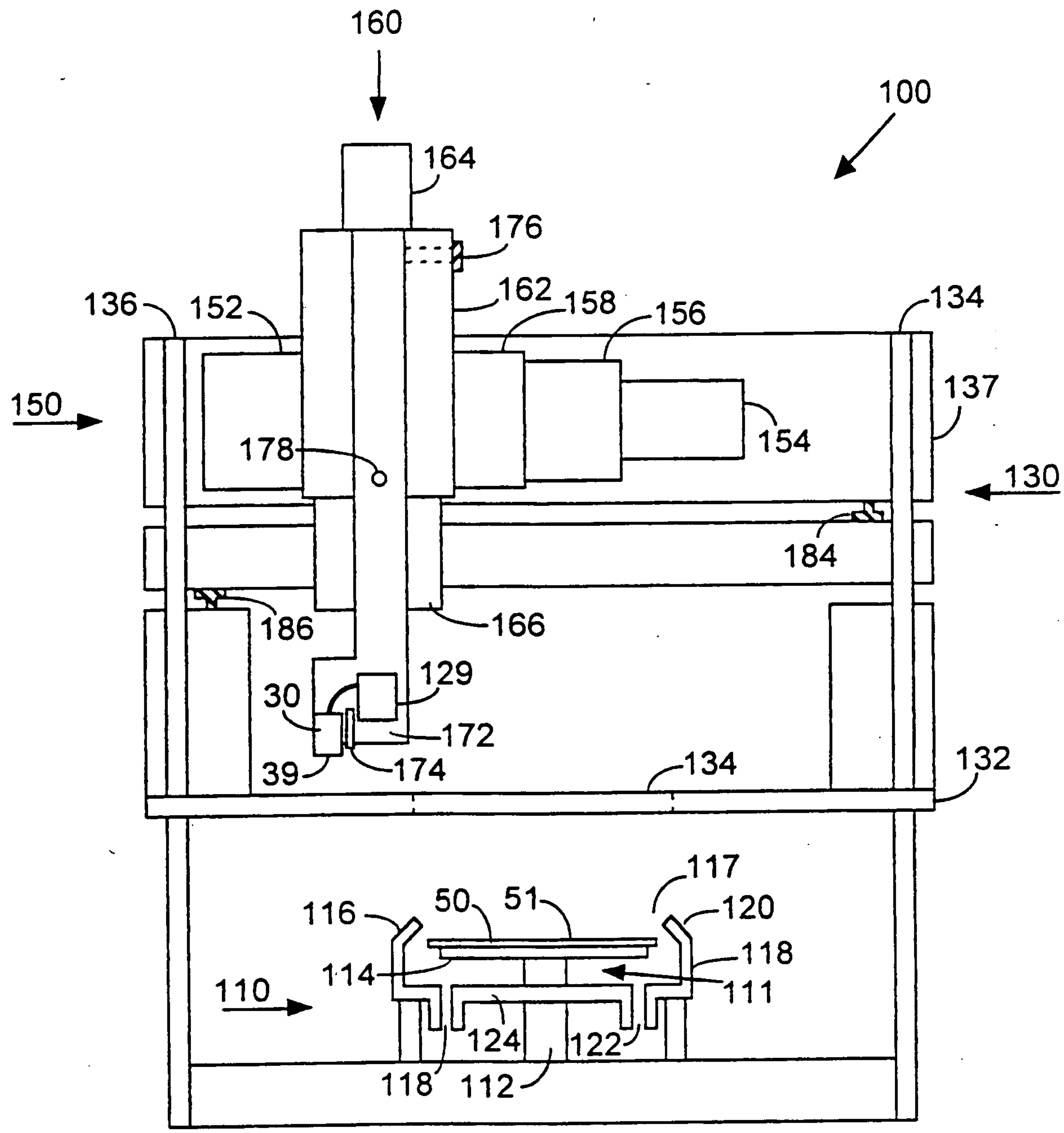


FIG. 11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111
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FIG. 12

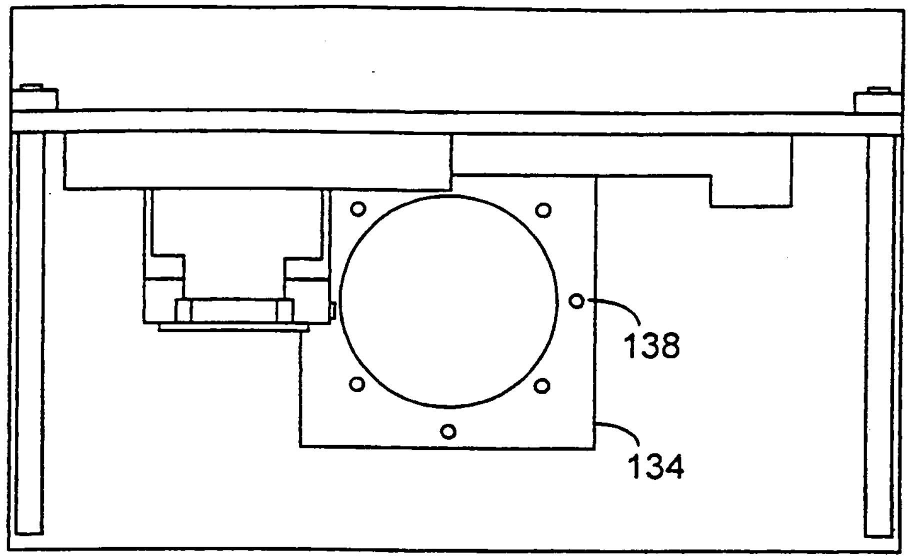
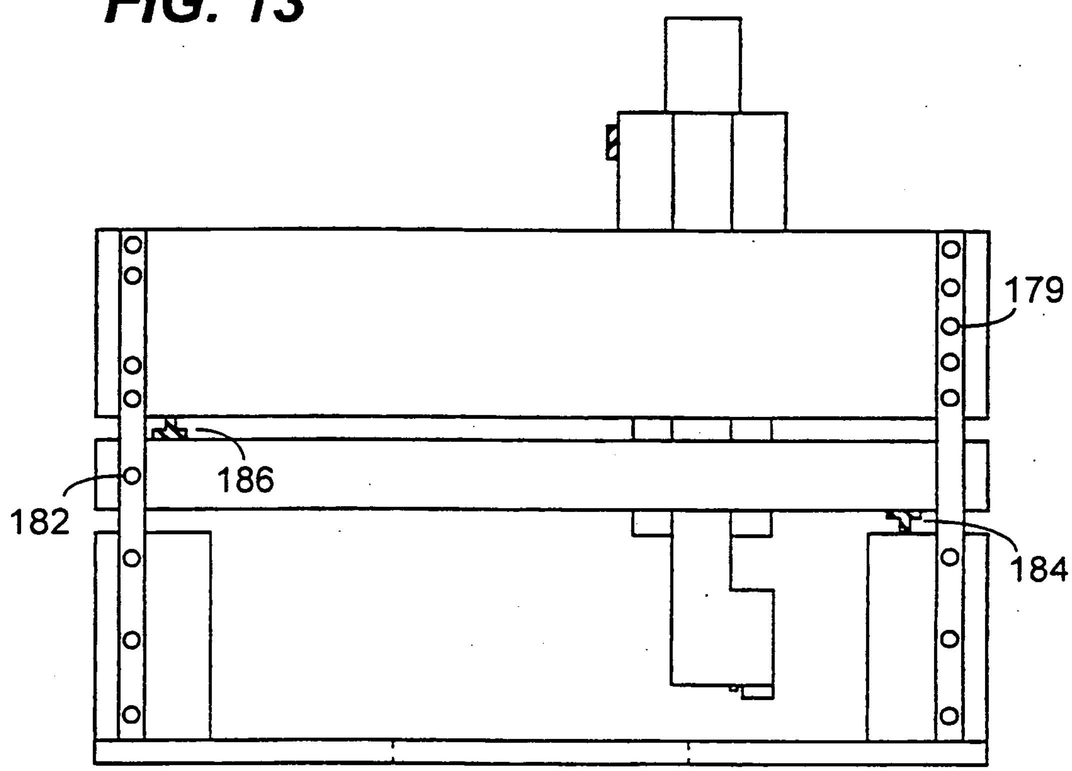


FIG. 13



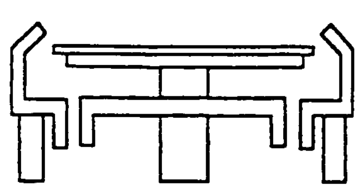
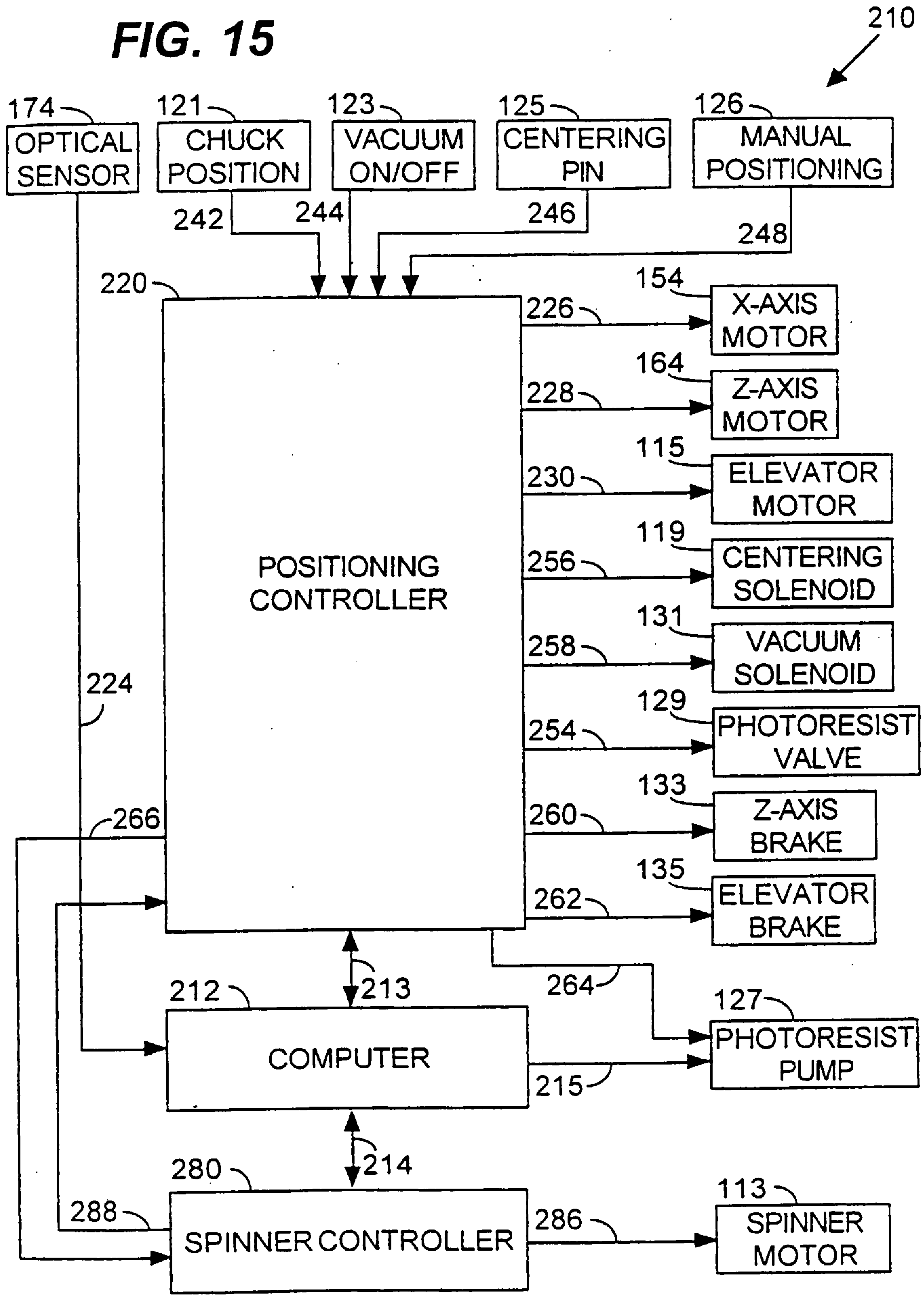


FIG. 14

FIG. 15


210
174
OPTICAL SENSOR
121
CHUCK POSITION
123
VACUUM ON/OFF
125
CENTERING PIN
126
MANUAL POSITIONING
242
244
246
248
220
POSITIONING CONTROLLER
226
228
230
256
258
254
260
262
154
X-AXIS MOTOR
164
Z-AXIS MOTOR
115
ELEVATOR MOTOR
119
CENTERING SOLENOID
131
VACUUM SOLENOID
129
PHOTORESIST VALVE
133
Z-AXIS BRAKE
135
ELEVATOR BRAKE
224
266
213
212
COMPUTER
264
127
PHOTORESIST PUMP
215
214
280
288
SPINNER CONTROLLER
286
113
SPINNER MOTOR

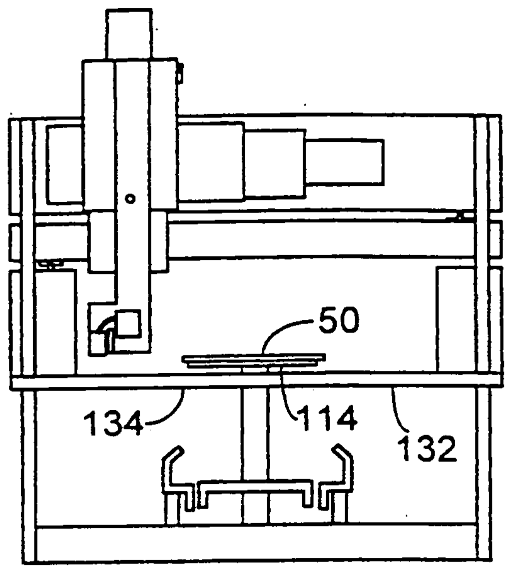


FIG. 16

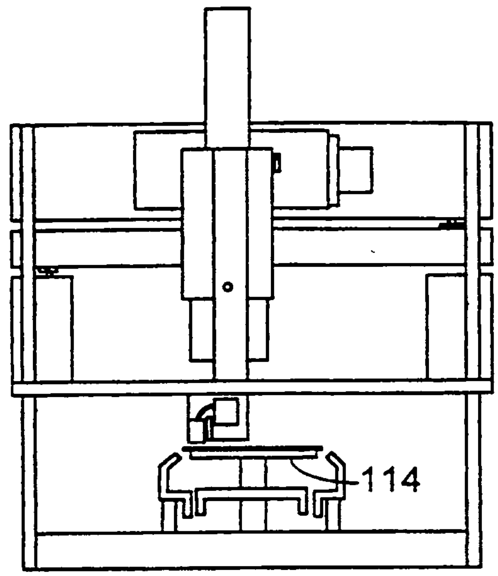


FIG. 17

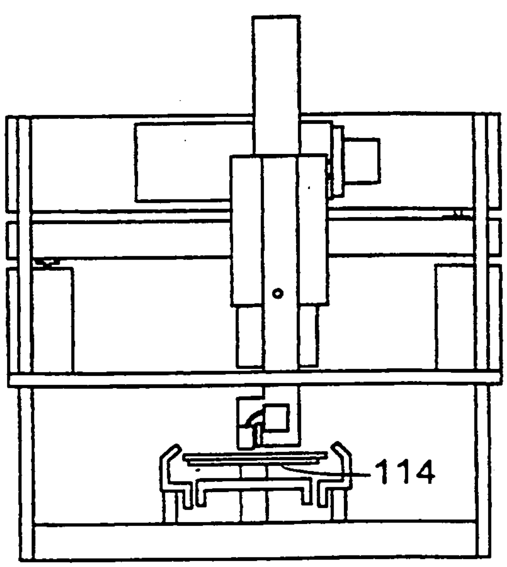


FIG. 18

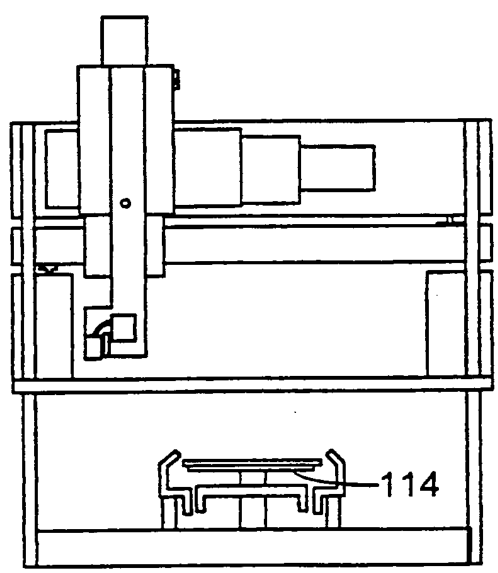


FIG. 19

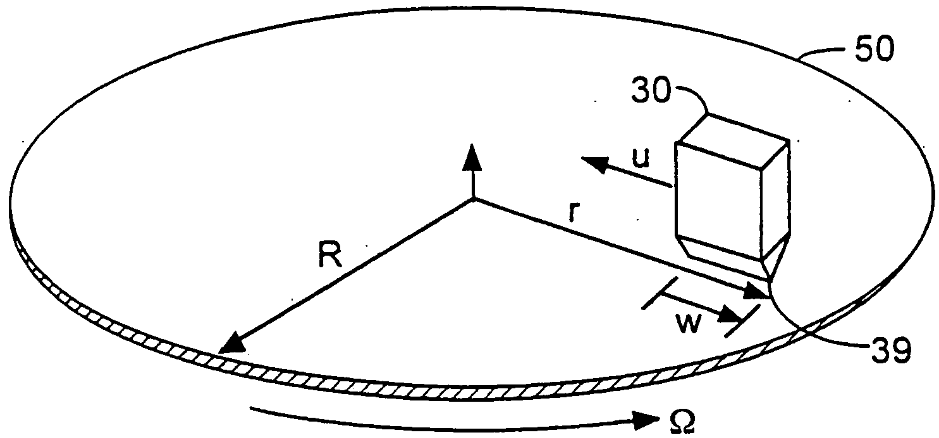


FIG. 20

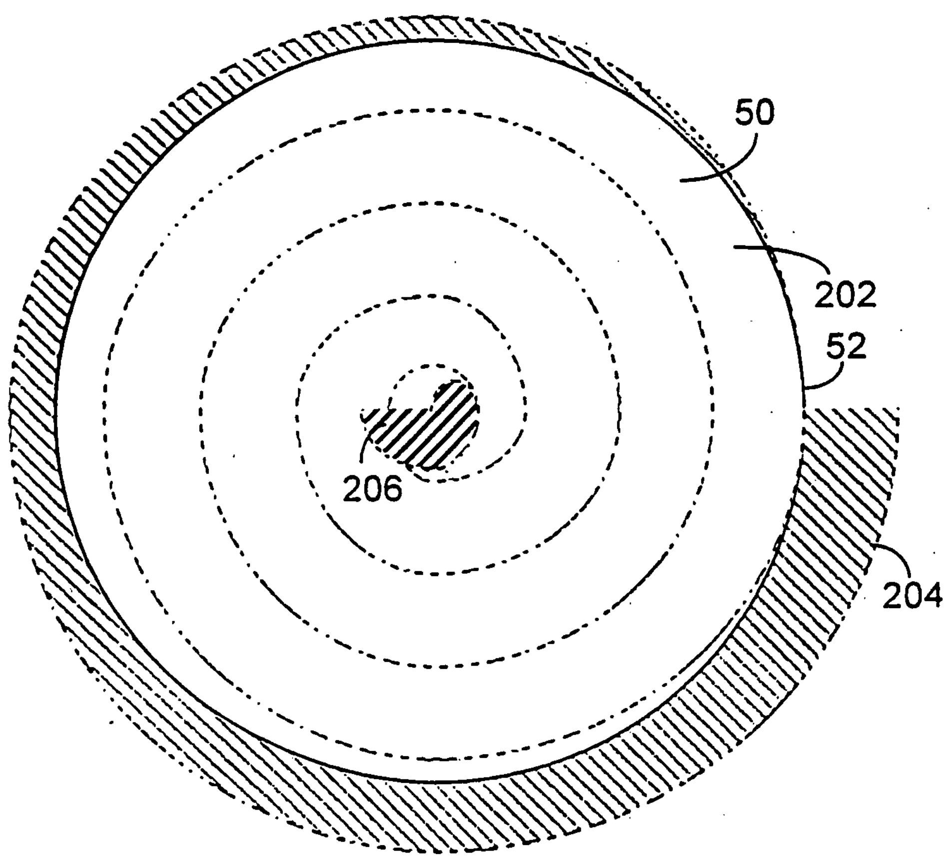


FIG. 21

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US98/11988

A. CLASSIFICATION OF SUBJECT MATTER

IPC(6) :BO5C 11/02; BO5D 3/12
US CL :427/8, 240, 356, 358; 118/52, 409, 410, 416, 712
According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

U.S. : 427/8, 240, 356, 358; 118/52, 409, 410, 416, 712

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	JP 08-168715 A (DAINIPPON SCREEN MFG CO LTD) 02 July 1996, see the abstract and figures.	1-21
Y	JP 63-301520 A (NEC CORP) 08 December 1988, see the abstract and figures.	1-21
Y	JP 03-22428 A (NEC KYUSHU LTD) 30 January 1991, see the abstract and figures.	2, 5-13, 15-21
A	JP 04-332116 A (MITSUBISHI ELECTRIC CORP) 19 Novemeber 1992, see the abstract.	1-21
A	US 5,532,192 A (ADAMS) 02 July 1996, see the abstract and figures.	1-21

☐ Further documents are listed in the continuation of Box C. ☐ See patent family annex.

* Special categories of cited documents:

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier document published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&" document member of the same patent family

Date of the actual completion of the international search

14 AUGUST 1998

Date of mailing of the international search report

21 SEP 1998

Name and mailing address of the ISA/US
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